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13. ABSTRACT *(Maximum 200 words)*

Over the past four years, the AFOSR Research Training grant has supported four graduate students and six undergraduate students. All of these students, especially the undergraduates, have benefited from their research training. They studied the links between the Sun and the cool stars in Algol-type binaries. These cool G – K solar-type secondary stars in short-period Algol-type binaries are expected to be magnetically-active because of their rapid rotation and outer convective layers. They display chromospheric and coronal activity more powerful than that of the Sun because their rotational periods have been increased by tidal interactions between the stars in a close binary. The P.I. and her students used several approaches to study magnetic activity in the Algol-type binaries. Their research included studies of the chromospheric contributions of the Hα line and other magnetically sensitive lines (e.g., Mg II); use of the image reconstruction technique called Doppler tomography; a long-term radio flare survey; a comparison of the characteristics of magnetic activity on the Sun and those observed from magnetically active binaries; and hydrodynamic simulations of gas flows in magnetically active binaries. The grant has produced 17 publications, including 7 refereed articles.

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Final Technical Report for AFOSR AASERT Grant F49620-94-1-0351

Principal Investigator: Mercedes T. Richards, University of Virginia

Project Title: Magnetic Activity in Algol Binaries

Project Period: 07-01-94 to 06-30-98

Summary of Research Experiences

Over the past four years, the AFOSR Research Training grant has been used to support eight students directly, and it supported research projects with two other students. There were four graduate students: Geary Albright, Mark Ratliff, Ronak Shah, Joshua Kempner; and six undergraduate students: Larissa Bowles, Erik Rosolowsky, Scot Russell, Larry Moore, Melinda Faris, and Ashley Graham. (see attached list). All of these students, especially the undergraduates, have benefited from their research training.

Under the AASERT grant, the P.I. supervised 3 students in Year 1 (Albright, Ratliff and Bowles), 5 students in Year 2 (Albright, Ratliff, Bowles, Russell, and Rosolowsky), 4 students in Year 3 (Shah, Rosolowsky, Faris, Moore), and 3 students in Year 4 (Kempner, Faris, Graham). These students have used several approaches to study magnetic activity on the rapidly-rotating cool components in short-period ($P < 6$ days) Algol-type binaries. The results for Algol binaries were compared with with those from magnetically active RS Canum Venaticorum binaries, e.g., HR 1099 (V711 Tau). The grant has produced 17 publications (see attached list) based on work described below.

The P.I. and Albright (graduate student), monitored and analyzed Hα spectra of short-period Algols, and they obtained 224 additional Hα spectra at Kitt Peak National Observatory (KPNO) in December, 1994. This brought the total to over 2000 spectra of 18 Algols. The P.I. and Albright also coordinated an international multiwavelength campaign in December 1994 to obtain simultaneous Hα spectra and 8.4 GHz radio continuum observations to determine the relative contributions of chromospheric emission associated with the magnetically-active secondary and the products of Roche-lobe overflow on the observed Hα line profile. Observations were obtained from KPNO, Green Bank Observatory (NRAO), and Ondřejov Observatory (with Dr. P. Koubský, Astronomical Institute, Academy of Sciences, Czech Republic). While no flares were reported during the simultaneous campaign, a subsequent long-term campaign which the P.I. initiated in January 1995 has been successful in detecting radio flares from two binaries (β Per, HR 1099) with the help of the Green Bank interferometer operated by the Naval Research Laboratories.

Bowles (undergraduate), and the P.I. used the Hα spectra to find the contributions to the hydrogen line from the chromosphere and the usual products of mass transfer. This was done with the aid of an image reconstruction technique called "Doppler Tomography" which is routinely used in medicine to reconstruct 3-dimensional images of parts of the human body from 2-dimensional CAT scans or X-ray images. When applied to binary stars, tomography produces 2-dimensional images of the sources of hydrogen in the orbital plane of each binary system, not in the usual spatial dimensions but in dimensions of velocity. The P.I. and Albright also found several sources of Hα emission, including evidence of chromospheres in the short-period Algol binaries. These studies have now provided the first convincing images of gas streams along the predicted gravitational path from the mass loser to the mass gainer in the Algols *and in the entire class of interacting binaries.* Moreover, they have produced the first images of chromospheres in the entire class of Algols, and found that the chromospheric emission

was generally weaker than all other sources of emission in the binary. Doppler tomograms were made from Hα spectra of 12 short-period Algol binaries (including one non-eclipsing system, CX Dra) as well as the RS CVn binary called HR 1099. Chromospheric emission was detected in 10 of these systems, most notably, β Per, RW Tau, TX UMa, RS Vul, and U Sge. In fact, the similarities between the tomograms of these latter Algols and HR 1099 are quite interesting, and have led to even stronger evidence in favor of a significant chromospheric component in the Hα line profile.

The P.I. and Moore (undergraduate) continued the analysis of Hα spectra of the short-period Algols U Sge and U CrB. They used the image reconstruction technique called "Doppler Tomography" to examine the time- and phase-dependence of the Hα emission in an attempt to isolate the chromospheric emission from these binaries. Moore and the P.I. attended the *Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, which was held in Cambridge. MA, in June 1997.

Shah (graduate student) assisted the P.I. in archiving the Hα spectra obtained at the National Solar Observatory and the Kitt Peak National Observatory since 1989.

Ratliff (graduate student) and the P.I. used hydrodynamic simulations (without magnetic fields) to demonstrate the process of Roche lobe overflow in two Algols, β Per and TT Hya. These simulations were used to interpret the Doppler maps generated from the observations. The radiative cooling of the gas was considered in these simulations, but the influence of magnetic fields was not included in these initial models. The simulations were displayed in both spatial and velocity dimensions and show little, if any, significant sources of emission associated with the cool magnetically active secondary star in each binary. The implication of this is that any substantial emission source associated with the velocity of the secondary star in the Doppler tomograms (derived from the observations) has to arise from the chromosphere and not as a result of mass transfer.

Bowles and Rosolowsky (undergraduates) assisted the P.I. in the investigation of the IUE database to search for evidence of magnetically sensitive lines in the ultraviolet spectrum (e.g., Mg II h+k). Once again, the spectrum of HR 1099 was used as an indicator of the appearance of similar lines in the Algols. Doppler maps of the Mg II h+k lines were made and compared with their optical counterpart at Hα. The maps were very similar. Since the uv spectra of the Algols do not display any obvious emission from magnetically sensitive lines, the stellar photospheric spectrum has to be removed before comparison with HR 1099.

The P.I. and Rosolowsky (undergraduate) used archival IUE spectra of the RS CVn binary, HR 1099, from 1978 to 1994 to obtain reconstructed Doppler images of the sources of chromospheric emission in the binary. Doppler tomograms were made from the magnetically-sensitive lines Mg h+k, C II, He II and Ly α lines. These maps were compared with their optical counterpart at Hα. The tomograms showed that the chromospheric emission sources were centered on or around the velocity of the magnetically active K star. The P.I. and Rosolowsky presented their results at two professional meetings in 1997.

Kempner (graduate student) and the P.I. extended this work to the ultraviolet spectra of U Sge, a short-period Algol. They analyzed the Si IV lines and found evidence of circumetellar gas flows associated with the process of Roche lobe overflow, but there was no evidence of any significant chromospheric contribution at this wavelength.

Faris, Graham (undergraduates) and the P.I. studied the differences between the characteristics of magnetic activity on the Sun and those observed from magnetically-active binaries. In the past, it has been useful to consider cool stars in binaries as scaled-up solar analogs, but it is now quite evident that there are distinct differences between the Sun and these other stars. It was unfortunate that Faris and then Graham could not complete their projects for medical reasons. Graham had to withdraw from the Astronomy-Physics program and graduated with a degree in Physics.

The P.I. and Russell (undergraduate) studied the 2.7 GHz and 8.1 GHz radio flare observations of four binaries to determine whether strong flares occurred at specific orbital phases. The 1972 – 1975 observations of two Algols (β Per and b Per) and two RS CVn binaries (AR Lac and UX Ari) were obtained at the NRAO Green Bank Observatory by D. Gibson. There was the expectation that tidal effects would enhance the flaring activity near phase 0.5 and 0.0, but the data showed no correlation with orbital phase.

The long-term campaign to monitor radio flares with the Green Bank interferometer has been very successful and is still in progress. Since January 1995, many strong flares have been detected from β Per (an Algol) and HR 1099 (an RS CVn binary). Several similarities were found between the strengths of the flares, and the flaring cycle in both systems.

In summary, the AASERT grant has provided these students with exposure to active research topics which resulted in publications that are of great interest to the astronomy community. Several of the students attended national or international conferences (Albright, Ratliff, Bowles, Rosolowsky, Moore) and presented papers. The lists of conference presentations and publications are included in this report. The research experiences of Bowles and Rosolowsky helped them to be accepted into good graduate schools. In all cases, the P.I. witnessed the excitement of discovery through the eyes of her students. For this alone, the award was a tremendous success.

Presentations at Meetings

"Doppler Tomography of Accretion Regions in Algols," International Conference to Celebrate the Centenary of the Royal Observatory, Edinburgh, on *Circumstellar Matter*, Edinburgh, Scotland, August 29 – September 2, 1994 (Richards, Albright, Bowles).

"Circumstellar Matter in Direct Impact Algol Systems," International Conference to Celebrate the Centenary of the Royal Observatory, Edinburgh, on *Circumstellar Matter*, Edinburgh, Scotland, August 29 – September 2, 1994 (Richards, Albright).

"Doppler Tomography of Accretion Regions in Algol Binaries," *185th Meeting of the American Astronomical Society*, Tucson, Arizona, January 8 – 12, 1995 (Richards, Albright, Bowles).

"Accretion Regions in Direct-Impact Algol Binaries," *185th Meeting of the American Astronomical Society*, Tucson, Arizona, January 8 – 12, 1995 (Albright, Richards).

"Hydrodynamical Simulations of Hα Emission in Algol Binaries," *187th Meeting of the American Astronomical Society*, San Antonio, Texas, January 14 – 18, 1996 (Ratliff, Richards).

"Hydrodynamical Simulations of Hα Emission in Algol Binaries," IAU Colloquium 163 on *Accretion Phenomena and Related Outflows*, Port Douglas, Queensland, New Zealand, July 15 – 19, 1996 (Ratliff, Richards).

"Doppler Tomography of Ultraviolet Spectra of the RS CVn Binary HR 1099," *189th Meeting of the American Astronomical Society*, Toronto, Canada, January 12 – 16, 1997 (Rosolowsky, Richards).

"Doppler Tomography of Ultraviolet Spectra of HR 1099," *Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, Cambridge, Massachusetts, July 15 – 19, 1997 (Richards, Rosolowsky).

"Dependence of Radio Flaring Activity on Orbital Phase in Archival Observations of Algol-type and RS CVn Binaries," *Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, Cambridge, Massachusetts, July 15 – 19, 1997 (Richards, Russell).

"Flaring Activity Cycles in β Per and HR 1099 from a 2GHz and 8GHz Radio Survey," *Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, Cambridge, MA, July 15 – 19, 1997 (Richards).

PUBLICATIONS resulting from AASERT Award

Refereed Articles

1. Richards, M. T., Albright, G. E., Bowles, L. M. 1995, "Doppler Tomography of the Gas Stream in Short-Period Algol Binaries," *Astrophys. J. Lett.*, **438**, L103 – L106
2. Albright, G. E., & Richards, M. T. 1996, "Doppler Tomography of Accretion Disks in Algol Binaries," *Astrophys. J. Lett.*, **459**, L99 – 102, and color Plate L14
3. Richards, M. T., & Albright, G. E. 1996, "Doppler Tomography of Chromospheres and Accretion Regions in Algol Binaries," in *Stellar Surface Structure*, ed. K. Strassmeier and J. Linsky (Dordrecht: Kluwer), 493 – 500
4. Richards, M. T., & Ratliff, M. A. 1998, "Hydrodynamic Simulations of Hα Emission in Algol Binaries," *Astrophys. J.*, **493**, 326 – 341 and color Plate 11
5. Kempner, J. C., & Richards, M.T. 1998, "Analysis of the Si IV Ultraviolet Spectra of U Sagittae," *Astrophys. J.*, **512**, in press (15 pages)
6. Richards, M. T., & Albright, G. E. 1998, "Morphologies of Hα Accretion Regions in Algol Binaries," submitted to *Astrophys. J.* (158 pages)
7. Richards, M.T., & Rosolowsky, E. W. 1998, "Doppler Tomograms of HR 1099 from Ultraviolet Spectra," submitted to *Astrophys. J.* (24 pages)

Conference Proceedings and Abstracts

8. Richards, M. T., Albright, G. E., & Bowles, L. M. 1994, "Doppler Tomography of Accretion Regions in Algol Binaries," *Bull. Am. Astron. Soc.*, **26**, 1345
9. Albright, G. E., & Richards, M. T. 1994, "Accretion Regions in Direct-Impact Algol Binaries," *Bull. Am. Astron. Soc.*, **26**, 1414
10. Ratliff, M. A., & Richards, M. T. 1995, "Hydrodynamical Simulations of Hα Emission in Algol Binaries," *Bull. Am. Astron. Soc.*, **27**, 1343
11. Richards, M. T., Albright, G. E., & Bowles, L. M. 1995, "Doppler Tomography of Accretion Regions in Algols," *Astrophys. Space Sci.*, **224**, 547 – 548
12. Albright, G. E., & Richards, M. T. 1995, "Circumstellar Matter in Direct Impact Algol Systems," *Astrophys. Space Sci.*, **224**, 415 – 416
13. Rosolowsky, E. W., & Richards, M. T. 1996, "Doppler Tomography of Ultraviolet Spectra of the RS CVn Binary HR 1099," *Bull. Am. Astron. Soc.*, **28**, 1375
14. Ratliff, M. A., & Richards, M. T. 1997, "Hydrodynamical Simulations of Hα Emission in Algol Binaries," in *Accretion Phenomena and Related Outflows*, ed. D. Wickramasinghe, G. Bicknell & L. Ferrario, ASP Conf. Ser., Vol. **121** (San Francisco: ASP), 785 – 786
15. Richards, M. T., Waltman, E. B., Foster, R. S., & Ghigo, F. 1998, "Flaring Activity Cycles in β Per and HR 1099 from a 2GHz and 8GHz Radio Survey," in *Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, eds. R.A. Donahue & J.A. Bookbinder, ASP Conf. Ser., Vol. **154** (San Francisco: ASP), CD 1546 – 1550
16. Richards, M. T., & Russell, S. 1998, "Dependence of Radio Flaring Activity on Orbital Phase in Archival Observations of Algol-type and RS CVn Binaries," in *Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, eds. R.A. Donahue & J.A. Bookbinder, ASP Conf. Ser., Vol. **154** (San Francisco: ASP), CD 1551 – 1559
17. Richards, M.T., & Rosolowsky, E. W. 1998, "Doppler Tomography of Ultraviolet Spectra of HR 1099," in *Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, eds. R.A. Donahue & J.A. Bookbinder, ASP Conf. Ser., Vol. **154** (San Francisco: ASP), CD 2038 – 2041

Students Supported by AASERT Award

Geary Albright
AASERT support: June 1994 – August 1996
Awarded Ph.D. (Astronomy), University of Virginia, in 1996.
Teaches science courses at a local high school and at Piedmont Virginia Community College.

Mark Ratliff
AASERT support: June 1995 – May 1996
Awarded M.A. (Astronomy), University of Virginia, in 1997.
Currently working at Princeton University with the JSTOR journal storage project.

Ronak Shah
AASERT support: September 1996 – December 1996
Awarded M.A. (Astronomy), University of Virginia, in 1997.
Currently enrolled in the Ph.D. program at the University of Virginia.

Joshua Kempner
AASERT support for project: September 1997 – May 1998
Awarded M.A. (Astronomy), University of Virginia, in 1998.
Currently enrolled in the Ph.D. program at the University of Virginia.

Larissa Bowles
AASERT support: June 1994 – August 1994; January 1996 – May 1996
Awarded B.A. (Astronomy-Physics), University of Virginia, in 1996.
Currently completing the M.S. degree (Astronomy), University of Toledo.
Expected to continue into the Ph.D. program.

Scot Russell
AASERT support for project: January 1996 – May 1996
Awarded B.A. (Astronomy-Physics), University of Virginia, in 1996.

Erik Rosolowsky
AASERT support: June 1996 – August 1996
Awarded B.A. (Physics), Swarthmore College, in 1998.
Will enter graduate program at Berkeley in 1999.

Larry Moore
AASERT support: June 1997 – August 1997
Awarded B.A. (Astronomy-Physics), University of Virginia, in 1997.
Currently working as a computer consultant.

Melinda Faris
AASERT support: January 1997 – December 1997
Expects to complete B.A. degree in 1999.

Ashley Graham
AASERT support: January 1998 – May 1998
Awarded B.A. (Physics), University of Virginia, in 1998.